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STRESS INTENSITY CALIBRATION OF A RING SPECIMEN USING A FINITE ELEMENT TECHNIQUE

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ABSTRACT

A finite element technique has been used to determine the stress intensity at the tip of a bore crack in a cylindrical fracture specimen. This technical note describes the detailed input for the computer programs which perform the stress analyses. Much of the preparatory work involves generating a suitable mesh of elements which represents the elastic properties of the specimen. The constraints which are imposed on the mesh geometry are described.

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STRESS INTENSITY CALIBRATION OF A RING SPECIMEN USING A FINITE ELEMENT TECHNIQUE

G. Clark and T.V. Rose

1. INTRODUCTION

Materials Research Laboratories are currently investigating the effect of residual stresses resulting from autofrettage on the growth of fatigue cracks originating at craze cracks on the bore surface of large-calibre gun barrels. This investigation makes use of ring specimens 25.4 mm thick, cut from 76 mm gun* barrel forgings; the rings are compressed across a diameter, and a fatigue crack grows from a starter notch in the bore surface immediately above the lower loading point. The stress-intensity at the tip of such a crack is known for rings having a diameter ratio of 0.5 [1,2]; in this case however, it was necessary to use specimens with a diameter ratio of 0.555, and this factor was believed to have a significant effect on the stress intensity calibration of the cracked specimen.

To obtain the stress-intensity calibration for the MRL specimen geometry, the specimen was modelled mathematically and subjected to a Finite-Element (FE) stress analysis. The computer programs used for this work were made available by ARL and are known collectively as DISMAL (DISplacement Method anALysis). This report describes the use of DISMAL for the ring specimen geometry.

2. DISMAL

The DISMAL programs for structural analysis were developed at the University of Sydney by Dr R.H. Keays [4]. Dr Keays later worked at ARL and modified the programs for operation on the ARL DEC PDP-10. Facilities for inserting a special crack tip element were added later [3] in order to provide better representation of the stress gradient near a crack tip. Full details on the general use of DISMAL are given in reference 4.

* Weapon for Australian Army Fire Support Vehicle

A-1

2.1 Mesh Generation

To analyse a specific geometry, it is first necessary to represent the structure as a network (or mesh) of elements. The ring specimen was modelled using a two-dimensional mesh consisting of quadrilaterals (QUAD4 elements), triangles (TRIM3) and one special element at the crack tip. The symmetry of the specimen permitted the use of a mesh representing only half of the ring, as shown in Fig. 1.

To generate the mesh, it is necessary to draw out the specimen on a scale sufficient for accurate identification of the element corners (or nodes), including features such as the fatigue crack and load-application points. The special element is then defined and consists of 10 nodes making a semicircle centred on the crack tip. The node points are separated by 20° and are placed at a radius 'r' where 'r' is half the crack length or half the remaining ligament, whichever is smaller. These nodes are numbered 1 to 10 clockwise and are linked consecutively. Two further semicircles of 10 nodes are positioned at radii 1.15r and 1.30r, and serve to transmit the displacements from the body of the structure to the special element; these are numbered 11 to 30 (clockwise, increasing radius). These nodes are linked to form two bands of quadrilaterals around the special element.

This procedure for designating the corners of quadrilaterals (and triangles where these are more suitable) is continued until the whole structure is represented. The semicircular arrangement of points 1 to 30 is not, in general, continued, although the following guide lines are followed.

(a) The area enclosed by each element should gradually increase with distance from the crack tip until a workable element size (typically 0.5% of the total area) is achieved.

(b) The numbering system used should ensure that the difference between the largest and smallest node numbers defining an element is minimised in order to reduce computing time. An acceptable band width was obtained with a node difference of 15.

(c) The smallest allowable included angle is 40° for quadrilaterals and 15° for triangular elements.

(d) Loads should be introduced via a series of elements of gradually increasing size.

2.2 Input to Programs - File "DATA"

A file "DATA" is constructed, containing all the information required to characterize the mesh and loading conditions. The format (including order) of this information is rigidly defined in the programs and any deviation from this format can produce results which contain errors. Appendix 1 is the DATA file for a ring specimen which contains a crack 0.2 of the wall thickness in length. The major features requiring care during construction of this file are described below.

(a) The program title must be the first line of data; a FORTRAN format of 18A4 is used, read with right justification, e.g. RING _555_A/W0.2.

(b) Units used in the program form the second line, in 2A3, 2X, 2A3 format, e.g. M M _ _ _ _ _ _ NEWTON.

(c) MASK is the third line, and suppresses the unused degrees of freedom for each node. The format is MASK _ _ _XYZ $R_xR_yR_z$ where XYZ represents displacement in the x, y and z directions, and R_x, R_y, R_z allow rotations about the three axes; a code 1 inhibits movement and 0 allows displacement, e.g. MASK _ _ _ 000111 allows movement of the nodes but no rotations.

An error was discovered in the existing program prohibiting the use of a two-dimensional mask i.e. 001111, and it was therefore necessary to insert the 'z' direction restriction after each node number.

(d) The fourth line defines the total number of points in the structure (and hence the number of lines following). Format is POINTS, 12X, I4.

(e) The following lines consist of information about each node in the mesh; number, degree of freedom and position (in a rectangular coordinate system). The format is I5, 2X, 6I1, 3F10.2, and nodes are inserted in ascending numerical order (in fact, the program re-numbers the nodes in input order, so it is necessary to take care with input to avoid the band-width problem outlined earlier).

In the example in Appendix 1, it should be noted that symmetry of the specimen requires the use of a y-direction restriction on those points along the symmetry axis and common to both halves of the specimen. It is also necessary to fix one point on the mesh in space to avoid translational movement of the whole specimen; in this case, point 377 (on the symmetry axis) was chosen.

(f) Following the last node description are two lines which define the material's elastic properties. The format is

MATERIAL, 17X, TITLE OR COMMENT (UP TO 17 CHARACTERS)
E15.0, F5.3, E15.0, 2E10.0

where the second line contains Young's Modulus, Poisson's Ratio, Shear modulus, maximum allowable stress in tension or compression, and maximum allowable shear stress. Default for the maximum allowable stresses is zero.

(g) The next section defines the special crack tip element; two lines are used, the first having the format 4A4, A2, 1X, I4, 4A4, A2

SPECIAL_ELEMENTS _ _ _ _ _ _ 1 _ _ CRACK_TIP

The second line is a mask used to define the degrees of freedom for each node point, in format I2, 60I1, the first term being the number of nodes in the element, the others being masks of a similar form to those used earlier. Only masks of 000111 or 000000 can be used; no z-direction constraint is allowed. The third line (I2, 10I5) defines the similarity and corner points of the special element; a second special element (identical in size and orientation) may be inserted by making SIM=01 for the second special element. Note that points are defined in an anti-clockwise direction.

(h) Printing of the element stiffness matrices and of detailed stresses may be switched off by the next two lines:

PRINT_ELSTIF_OFF
PRINT_STRESS_OFF

(i) The quadrilateral element control line and element definitions follow, in the format

4A4, A2, 1X, I4, 2X, 4A4, A2
I2, 4I5, F10.4, E10.1, F5.3, E10.1

where the first line contains

QUADRI _ _ _ _ _ _ QUAD4 _ _ _ 307

The second 4A4, A2 is available for comments which will appear in the output text, and the second line contains (in order) similarity, the four node numbers (anticlockwise), thickness (assumed to be unchanged if left blank), Young's Modulus, Poisson's Ratio, and Shear Modulus (the last three defaulting to the values in the previous MATERIAL statement). The second format is repeated for each element of the specified type.

(j) Triangular element control line and definitions follow a similar format (with 3I5 stead of 4I5). Thickness may be left blank, defaulting to the previously-defined value.

(k) If the structure has been fully defined, the line END _ _ STRUCTURE is inserted.

(l) Any number of load cases may now be inserted, in the format

LOADS, 14X, I4, 2X, 4A4, A2
I5, 6F10.02

where the first line contains the number of loads in the load case, and the load case name, and the second line(s) contain the number of the node(s) at which load is applied, the forces in x, y, z directions, and moments M_x, M_y, M_z.

(m) The line END _ _ LOADS terminates the data file.

2.3 Input to Programs - File "CDATA"

A second input file is required to define the properties of the crack tip special element. The file contains

Number of nodes in the special element
Young's modulus, Poisson's ratio, thickness
  and radius of the element
Angular separate of nodes (in radians)
Integration step size
The number of terms in the stress function
Global coordinates of local axes $X_i Y_i Z_i$ (i=1,2,3).

Further details of these parameters are given in reference 5, and an example of file CDATA is given in Appendix 2.

3. DATA CHECKING AND INPUT

Two programs are used to check the input data. The first, DIPLOT creates a plot of the mesh as described in DATA, and this plot may be inspected for continuity and geometric anomalies. An example of the dialogue required to run DIPLOT is given in reference 4.

The second program INPUTS performs some checking in preparation for determination of the stiffness matrix. If there are no errors a communication file DTALK.TMP is created on disk. If no such file is produced, information on the errors in DATA is given in file PRINT1.LST.

If all is in order, the programs which make up DISMAL are run as a BATCH job (too much core is required for running the programs individually from MONITOR). The batch control program for execution of DISMAL is contained in Appendix 3.

4. RESULTS AND DISCUSSION

The crack tip stress intensity is given in the output file PRINT3.LST. For this particular geometry, the symmetry condition used to reduce the number of elements implies that the load applied to the half-ring is half of that which would be applied to the full ring.

Meshes representing crack lengths between 0.1 and 0.9 of the ring wall thickness (W) were processed. The values of stress intensity (K) obtained for a load P are given in Table I, in the form of the dimensionless parameter Y where B is the ring thickness and

$$K = \frac{PY}{B\sqrt{W}}$$

For ease of use, a polynomial was fitted to this data, giving the relation

$$Y = 9.8054(a/W)^{0.5} - 25.0044(a/W) + 54.6356(a/W)^{1.5} - 78.330(a/W)^{2} + 62.0963(a/W)^{2.5} - 21.7418(a/W)^{3}$$

This polynomial was used [6] to determine the relationship between fatigue crack growth rate and crack tip stress intensity in ring specimens.

5. CONCLUSION

A finite element technique has been used to determine the stress intensity at the tip of a bore crack in a ring specimen loaded in compression across the diameter; various crack lengths were considered, and the results have been presented in a polynomial form.

Table I   Results of Analysis

Crack Length	$Y = KB\sqrt{W}/P$
0.1 W	1.717
0.2 W	2.073
0.3 W	2.273
0.4 W	2.376
0.5 W	2.433
0.6 W	2.400
0.7 W	2.312
0.8 W	2.150
0.9 W	1.865

REFERENCES

1. Jones, A.T., "A Radially Cracked Cylindrical Fracture Toughness Specimen", Engineering Fracture Mechanics, 6 435-446 (1974).

2. Grandt, A.F., Jr, "Evaluation of a Cracked Ring Specimen for Fatigue Testing under Constant Range in Stress Intensity Factor", Proc. Internat. Conf. Fracture Mechanics and Technology, Hong Kong, March 21-25, 1977.

3. Jones, R. and Callinan, R.J., "A Special Crack Tip Element for Three-Dimensional Crack Problems", Structures Report 374, Aeronautical Research Laboratories, Melbourne (November 1978).

4. Callinan, R.J., "Users Guide to DISMAL - A General Purpose Structural Analysis Program", Structures and Materials Tech. Memorandum 227, Aeronautical Research Laboratories, Melbourne (January 1975).

5. Callinan, R.J., "Programs for Calculating Stress Intensity Factors in Structures having Cracked Sheet Elements", Structures Tech. Memorandum 244, Aeronautical Research Laboratories, Melbourne (1976).

6 Clark, G., "Experimental Determination of Stress-Intensity in a Cracked Cylindrical Specimen", Report MRL-R-774, Materials Research Laboratories, Melbourne (1980).

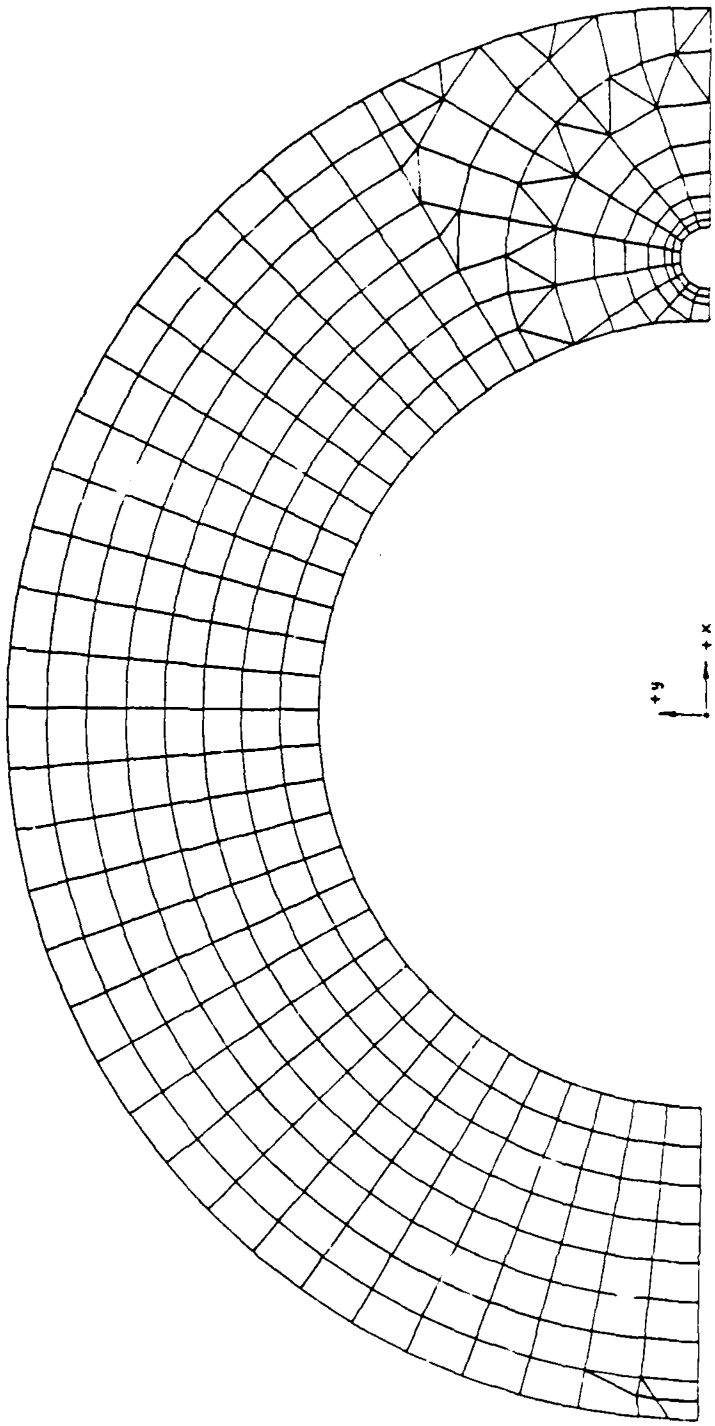

Figure 1. Finite Element Mesh for half ring containing a bore crack 0.2 of the wall thickness in length.

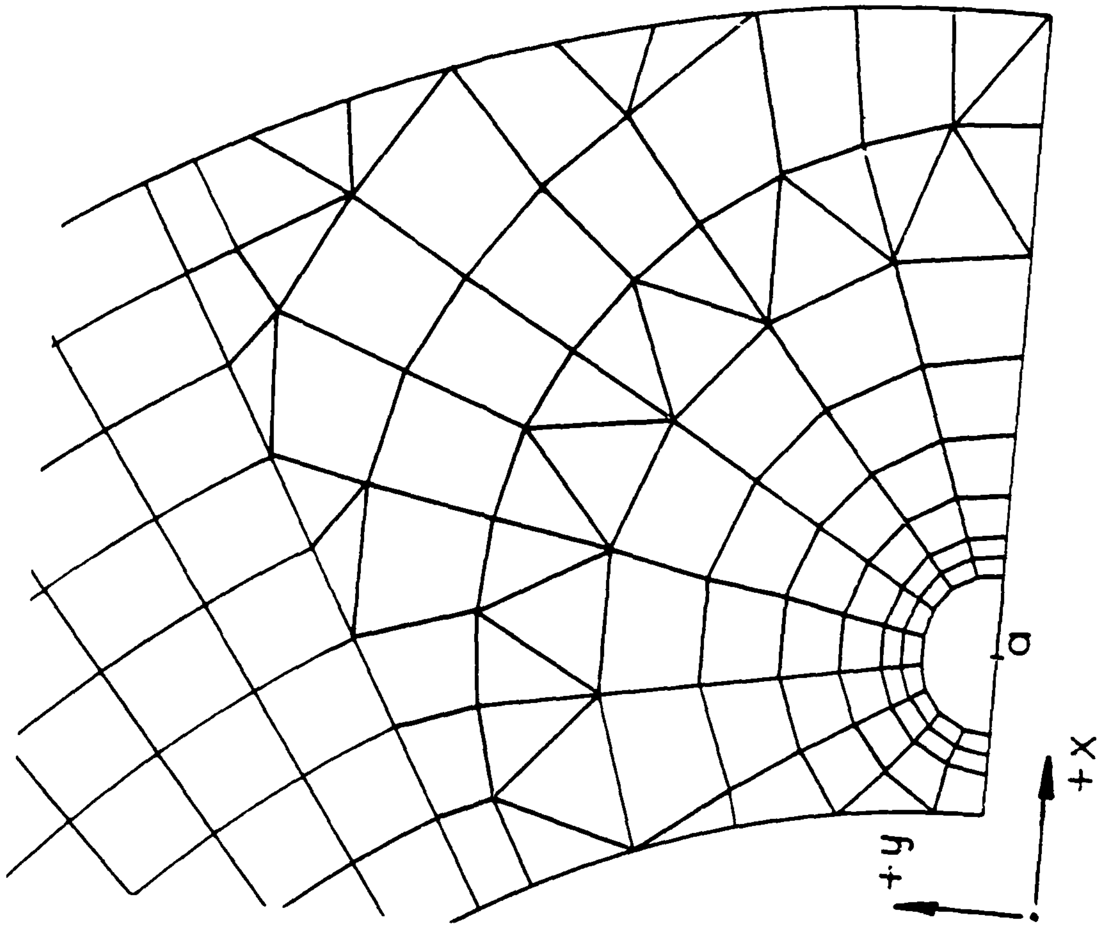

Figure 2. Crack tip region of mesh shown in Fig. 1. Crack tip is at "a".

DATA (APPENDIX 1)

RING 0.555 R A/W=0.2 with modified points
MM NEWTONS
MASK 000111
POINTS 377

1	1	108.000	0.000
2	1	108.482	2.736
3	1	109.872	5.142
4	1	112.000	6.928
5	1	114.611	7.878
6	1	117.389	7.878
7	1	120.000	6.928
8	1	122.128	5.142
9	1	123.518	2.736
10	11	124.000	0.000
11	1	106.000	0.000
12	1	106.603	3.420
13	1	108.340	6.428
14	1	111.000	8.660
15	1	114.264	9.848
16	1	117.736	9.848
17	1	121.000	8.660
18	1	123.660	6.428
19	1	125.397	3.420
20	11	126.000	0.000
21	1	104.000	0.000
22	1	104.724	4.104
23	1	106.807	7.713
24	1	110.000	10.392
25	1	113.916	11.818
26	1	118.084	11.818
27	1	122.000	10.392
28	1	125.193	7.713
29	1	127.276	4.104
30	11	128.000	0.000
31	1	100.000	0.000
32	1	99.870	5.000
33	1	103.600	10.400
34	1	108.000	14.000
35	1	113.200	16.000
36	1	118.800	16.000
37	1	124.000	14.000
38	1	128.400	10.400
39	1	131.200	5.600
40	11	132.000	0.000
41	1	98.870	15.000
42	1	104.800	19.200
43	1	112.000	22.000
44	1	120.000	22.000
45	1	127.200	19.200
46	1	132.800	14.400
47	1	136.800	7.600
48	11	138.000	0.000
49	1	96.820	25.000
50	1	102.000	28.000
51	1	110.800	30.000
52	1	121.000	30.000

53	1	131.200	26.000
54	1	138.800	19.600
55	1	144.000	10.400
56	11	146.000	0.000
57	1	93.670	35.000
58	1	108.800	40.000
59	1	123.200	40.000
60	1	136.400	34.800
61	1	146.800	26.000
62	1	154.000	14.000
63	11	156.000	0.000
64	1	89.300	45.000
65	1	97.600	49.600
66	1	106.600	52.000
67	1	116.000	52.800
68	1	125.200	52.000
69	1	134.400	49.600
70	1	142.400	45.600
71	1	150.000	40.000
72	1	156.000	34.000
73	1	161.600	26.000
74	1	165.200	18.000
75	1	168.000	9.200
76	11	168.800	0.000
77	11	180.000	0.000
78	1	179.720	10.000
79	1	178.890	20.000
80	1	177.480	30.000
81	1	175.500	40.000
82	1	166.000	42.000
83	1	158.400	50.000
84	1	148.800	56.800
85	1	139.200	62.000
86	1	127.600	64.800
87	1	172.920	50.000
88	1	169.710	60.000
89	1	156.000	68.800
90	1	144.000	75.200
91	1	165.830	70.000
92	1	161.250	80.000
93	1	150.000	80.000
94	1	158.670	85.000
95	1	86.600	50.000
96	1	95.260	55.000
97	1	103.920	60.000
98	1	112.580	65.000
99	1	121.240	70.000
100	1	129.900	75.000
101	1	138.560	80.000
102	1	147.220	85.000
103	1	155.880	90.000
104	1	81.920	57.360
105	1	90.110	63.070
106	1	98.300	68.830
107	1	106.490	74.560
108	1	114.680	80.300

109	1	122.870	86.040
110	1	131.060	91.770
111	1	139.260	97.510
112	1	147.450	103.240
113	1	76.600	64.280
114	1	84.260	70.710
115	1	91.930	77.130
116	1	99.590	83.560
117	1	107.250	89.990
118	1	114.910	96.420
119	1	122.570	102.850
120	1	130.230	109.270
121	1	137.890	115.700
122	1	70.710	70.710
123	1	77.780	77.780
124	1	84.850	84.850
125	1	91.920	91.920
126	1	98.990	98.990
127	1	106.060	106.070
128	1	113.140	113.140
129	1	120.210	120.210
130	1	127.280	127.280
131	1	64.280	76.600
132	1	70.710	84.260
133	1	77.130	91.930
134	1	83.560	99.590
135	1	89.990	107.250
136	1	96.420	114.910
137	1	102.850	122.570
138	1	109.270	130.230
139	1	115.700	137.890
140	1	57.360	81.920
141	1	63.090	90.110
142	1	68.830	98.300
143	1	74.560	106.490
144	1	80.300	114.680
145	1	86.040	122.870
146	1	91.770	131.060
147	1	97.510	139.260
148	1	103.240	147.450
149	1	50.000	86.600
150	1	55.000	95.260
151	1	60.000	103.920
152	1	65.000	112.580
153	1	70.000	121.240
154	1	75.000	129.900
155	1	80.000	138.560
156	1	85.000	147.220
157	1	90.000	155.880
158	1	42.260	90.630
159	1	46.490	99.690
160	1	50.710	108.760
161	1	54.940	117.820
162	1	59.170	126.880
163	1	63.390	135.950
164	1	67.620	145.010

5	1	71.850	154.070
6	1	76.070	163.140
7	1	34.200	93.970
8	1	37.620	103.370
9	1	41.040	112.760
0	1	44.460	122.160
1	1	47.880	131.560
2	1	51.300	140.950
3	1	54.720	150.350
4	1	58.140	159.750
5	1	61.560	169.140
6	1	25.880	96.590
7	1	28.470	106.250
8	1	31.060	115.910
9	1	33.650	125.570
0	1	36.230	135.230
1	1	38.820	144.890
2	1	41.410	154.550
3	1	44.000	164.210
4	1	46.590	173.870
5	1	17.360	98.480
6	1	19.100	108.330
7	1	20.840	118.180
8	1	22.570	128.030
9	1	24.310	137.870
0	1	26.050	147.720
1	1	27.780	157.570
2	1	29.520	167.420
3	1	31.260	177.270
4	1	8.720	99.620
5	1	9.590	109.580
6	1	10.460	119.540
7	1	11.330	129.510
8	1	12.200	139.470
9	1	13.070	149.430
0	1	13.940	159.390
1	1	14.820	169.350
2	1	15.690	179.320
3	1	0.000	100.000
4	1	0.000	110.000
5	1	0.000	120.000
6	1	0.000	130.000
7	1	0.000	140.000
8	1	0.000	150.000
9	1	0.000	160.000
0	1	0.000	170.000
1	1	0.000	180.000
2	1	-8.720	99.620
3	1	-9.590	109.580
4	1	-10.460	119.540
5	1	-11.330	129.510
6	1	-12.200	139.470
7	1	-13.070	149.430
8	1	-13.940	159.390
9	1	-14.820	169.350
0	1	-15.690	179.320

21	1	-17.360	98.480
22	1	-19.100	108.330
23	1	-20.840	118.180
24	1	-22.570	128.030
25	1	-24.310	137.870
26	1	-26.050	147.720
27	1	-27.780	157.570
28	1	-29.520	167.420
29	1	-31.260	177.270
30	1	-25.880	96.590
31	1	-28.470	106.250
32	1	-31.060	115.910
33	1	-33.650	125.570
34	1	-36.230	135.230
35	1	-38.820	144.890
36	1	-41.410	154.550
37	1	-44.000	164.210
38	1	-46.590	173.870
39	1	-34.200	93.970
40	1	-37.620	103.370
41	1	-41.040	112.760
42	1	-44.460	122.160
43	1	-47.880	131.560
44	1	-51.300	140.950
45	1	-54.720	150.350
46	1	-58.140	159.750
47	1	-61.560	169.140
48	1	-42.260	90.630
49	1	-46.490	99.690
50	1	-50.710	108.760
51	1	-54.940	117.820
52	1	-59.170	126.880
53	1	-63.390	135.950
54	1	-67.620	145.010
55	1	-71.850	154.070
56	1	-76.070	163.140
57	1	-50.000	86.600
58	1	-55.000	95.260
59	1	-60.000	103.920
60	1	-65.000	112.580
61	1	-70.000	121.240
62	1	-75.000	129.900
63	1	-80.000	138.560
64	1	-85.000	147.220
65	1	-90.000	155.880
66	1	-57.360	81.920
67	1	-63.090	90.110
68	1	-68.830	98.300
69	1	-74.560	106.490
70	1	-80.300	114.680
71	1	-86.040	122.870
72	1	-91.770	131.060
73	1	-97.510	139.260
74	1	-103.240	147.450
75	1	-64.280	76.600
76	1	-70.710	84.260

277	1	-77.130	91.930
278	1	-83.560	99.590
279	1	-89.990	107.250
280	1	-96.420	114.910
281	1	-102.850	122.570
282	1	-109.270	130.230
283	1	-115.700	137.890
284	1	-70.710	70.710
285	1	-77.780	77.780
286	1	-84.850	84.850
287	1	-91.920	91.920
288	1	-98.990	98.990
289	1	-106.070	106.070
290	1	-113.140	113.140
291	1	-120.210	120.210
292	1	-127.280	127.280
293	1	-76.600	64.280
294	1	-84.260	70.710
295	1	-91.930	77.130
296	1	-99.590	83.560
297	1	-107.250	89.990
298	1	-114.910	96.420
299	1	-122.570	102.850
300	1	-130.230	109.270
301	1	-137.890	115.700
302	1	-81.920	57.360
303	1	-90.110	63.090
304	1	-98.300	68.830
305	1	-106.490	74.560
306	1	-114.680	80.300
307	1	-122.870	86.040
308	1	-131.060	91.770
309	1	-139.260	97.510
310	1	-147.450	103.240
311	1	-86.600	50.000
312	1	-95.260	55.000
313	1	-103.920	60.000
314	1	-112.580	65.000
315	1	-121.240	70.000
316	1	-129.900	75.000
317	1	-138.560	80.000
318	1	-147.220	85.000
319	1	-155.880	90.000
320	1	-90.630	42.260
321	1	-99.690	46.490
322	1	-108.760	50.710
323	1	-117.820	54.940
324	1	-126.880	59.170
325	1	-135.950	63.390
326	1	-145.010	67.620
327	1	-154.070	71.850
328	1	-163.140	76.070
329	1	-93.970	34.200
330	1	-103.370	37.620
331	1	-112.760	41.040
332	1	-122.160	44.460

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 35     1     -150.350      54.720
 36     1     -159.750      58.140
 37     1     -169.140      61.560
 38     1      -96.590      25.880
 39     1     -106.250      28.470
 40     1     -115.910      31.060
 41     1     -125.570      33.650
 42     1     -135.230      36.230
 43     1     -144.890      38.820
 44     1     -154.550      41.410
 45     1     -164.210      44.000
 46     1     -173.870      46.590
 47     1      -98.480      17.360
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350     1     -128.030      22.570
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360     1     -139.470      12.200
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377   111     -180.000       0.000
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INT STRESS OFF
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    12      2      3     13
    13      3      4     14
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  363   354   364
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   89    91    92
   89    93    90
  100    90   101
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    98    86    99
D   STRUCTURE
ADS                     1   .1
  1               100.0
ADS                     1   .77
 77   -100.0
ADS                     1    11
 11               100.0
ADS                     1   .21
 21               100.0
ADS                     1    31
 31               100.0
D   LOADS
```

CDATA (APPENDIX 2))

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0.01
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1.,0.,0.
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BLOKK.CTL (APPENDIX 3)

```
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.R PIP
*DSK:DATA=DATA[3600,3613]
*DSK:/X=[3600,3613]ELSTIF.EXE
*DSK:/X=[3600,3613]STRESS.EXE
*DSK:CDATA=[3600,3613]CDATA
*DSK:/X=[3600,3613]ASSOLX.EXE,INPUTX.EXE
*DSK:/X=[3600,3613]CRACK3.EXE
.CHKPNT A1
A1::.RU CRACK3
.CHKPNT A2
A2::.RU INPUTX
.CHKPNT A3
A3::.RU ELSTIF
.CHKPNT A4
A4::.RU ASSOLX
.CHKPNT A5
A5::.RU STRESS
.R PRINT
*DATA,CDATA,PRINT1.LST/P(50),PRINT3.LST/P(400)
.R PRINT
*HELL
.DEL *.*
```

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DOCUMENT CONTROL DATA SHEET

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TITLE

Stress intensity calibration of a ring specimen using a finite element technique

AUTHOR(S)	CORPORATE AUTHOR
G. Clark and T.V. Rose	Materials Research Laboratory Defence Science & Technology Organisation PO Box 50 Ascot Vale Victoria 3032

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ANNOUNCEMENT

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KEYWORDS

Finite elements	Stress analysis	Calibrating
Crack propagation	Computer programs	Elastic properties

SUBJECT GROUPS 0041K

ABSTRACT

A finite element technique has been used to determine the stress intensity at the tip of a bore crack in a cylindrical fracture specimen. This technical note describes the detailed input for the computer programs which perform the stress analyses. Much of the preparatory work involves generating a suitable mesh of elements which represents the elastic properties of the specimen. The constraints which are imposed on the mesh geometry are described.

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